

# 同步电机改进模型等效电路的简化<sup>\*</sup>

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**摘要** 当建立同步电机完整的模型时, 需计及励磁绕组与阻尼绕组之间的互漏感. 互漏感的引入, 使同步电机的解析分析计算变得非常复杂, 致使传统的分析计算公式失效. 因此提出定子侧和转子侧的变换条件, 对引入励磁绕组与阻尼绕组之间互漏感后的同步电机(改进模型), 进行适当的简化. 这样, 使得简化后的模型与不计互漏感的传统同步电机模型相似, 从而可利用传统模型的解析方法及其公式分析计算.

**关键词** 同步电机, 等效电路, 网络变换

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## 1 简化方法与条件

图1、2为不计及励磁组与阻尼绕组之间互漏感时, 同步电机直、交轴模型的等效电路. 在同步电机传统的过渡过程分析中, 运算电抗起着重要的作用, 直轴运算电抗 $X_d(P)$ <sup>[1]</sup>为

$$X_d(P) = (T_d P + 1)(T_d' P + 1) / (T_{d0} P + 1)(T_{d0}' P + 1), \quad (1)$$

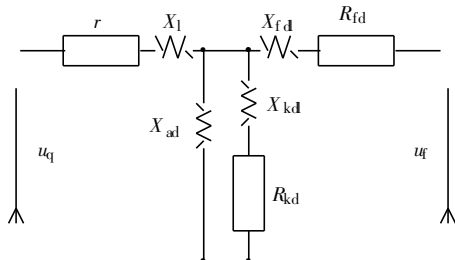


图1 传统的直轴等效电路

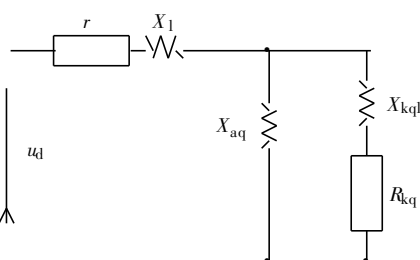


图2 传统的交轴等效电路

当计及励磁绕组与阻尼绕组之间的互漏感时, 其改进的同步电机直轴等效电路如图3所示<sup>[2,3]</sup>, 交轴等效电路仍如图2所示. 使用改进的同步电机模型计算动态特性非常复杂, 时间常数难以确定, 以致无法给出利用时间常数分析动态特性的直轴运算电抗 $X_d(P)$ 的解析表达式. 为了简化动态分析计算, 对图3电路作出等效变换. 即将图3中 $X_l1$ ,  $X_{ad}$ ,  $X_{fd}$ 所构成的T型网络变换为 $\Gamma$ 型网络(图4), 其变换条件有两点. (1) 保持定子端口电压、电流不变, 即

$$u_1 = u_1, \quad i_1 = i_1. \quad (2)$$

(2) 保持变换网络转子侧的功率不变, 即

$$u_2 i_2 = u_2 i_2, \quad u_2 i_4 = u_2 i_4, \quad u_3 i_3 = u_3 i_3. \quad (3)$$

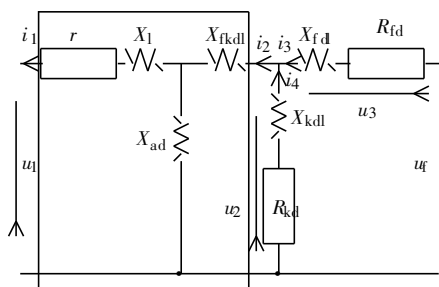


图3 改进的直轴等效电路

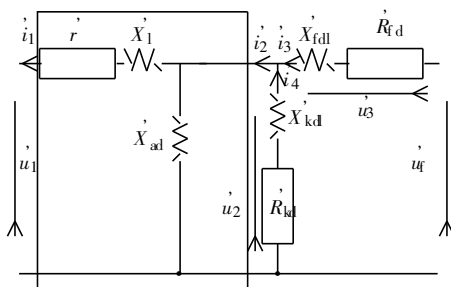


图4 直轴简化等效电路

## 2 简化电路的参数确定

应用变换条件式(2), (3), 来确定图4简化电路的参数. 由图3, 4电路分别有

$$\dot{U}_1 = [r + j(X_1 + X_{ad})] \dot{I}_1 - jX_{ad} \dot{I}_2, \quad \dot{U}_1 = [r' + j(X_1' + X_{ad}')] \dot{I}_1' - jX_{ad}' \dot{I}_2'. \quad (4)$$

令  $r + j(X_1 + X_{ad}) = r' + j(X_1' + X_{ad}')$ , 则  $r = r'$ , 从而可得出

$$X_1 + X_{ad} = X_1' + X_{ad}'. \quad (5)$$

再由式(2)得  $X_{ad} \dot{I}_2 = X_{ad}' \dot{I}_2'$ , 即

$$\dot{I}_2' / \dot{I}_2 = X_{ad} / X_{ad}' \triangleq K. \quad (6)$$

将  $X_{ad}' = K X_{ad}$  代入式(5), 得

$$X_1 = X_1' + X_{ad}' - X_{ad} = X_1' + (1 - K) X_{ad}. \quad (7)$$

由式(3)中  $u_2 i_2 = u_2 i_2$ , 即  $\dot{U}_2 \dot{I}_2^* = \dot{U}_2' \dot{I}_2'^*$ , 可得

$$\dot{U}_2' / \dot{U}_2 = \dot{I}_2^* / \dot{I}_2'^* = 1/K, \quad (8)$$

而由式(3)中  $u_2 i_4 = u_2 i_4$ , 即  $\dot{U}_2 \dot{I}_4^* = \dot{U}_2' \dot{I}_4'^*$ , 也可得

$$\dot{I}_4' / \dot{I}_4 = \dot{U}_2^* / \dot{U}_2'^* = K. \quad (9)$$

因此,  $R_{kd} + jX_{kdl} = \dot{U}_2' / \dot{I}_4' = K^2 \dot{U}_2 / \dot{I}_4 = K^2 (R_{kd} + jX_{kdl})$ , 即

$$R_{kd} = K^2 R_{kd}, \quad X_{kdl} = K^2 X_{kdl}. \quad (10)$$

由  $\dot{I}_3 = \dot{I}_2 - \dot{I}_4 = K(\dot{I}_2' - \dot{I}_4') = K \dot{I}_3'$ , 可得

$$\dot{I}_3' / \dot{I}_3 = K, \quad (11)$$

而由式(3)中  $u_3 i_3 = u_3 i_3$ , 即  $\dot{U}_3 \dot{I}_3^* = \dot{U}_3' \dot{I}_3'^*$ , 可得

$$\dot{U}_3' / \dot{U}_3 = \dot{I}_3^* / \dot{I}_3'^* = K. \quad (12)$$

因此,  $R_{fd} + jX_{fdl} = \dot{U}_3' / \dot{I}_3' = K^2 \dot{U}_3 / \dot{I}_3 = K^2 (R_{fd} + jX_{fdl})$ , 即

$$R_{fd} = K^2 R_{fd}, \quad X_{fdl} = K^2 X_{fdl}. \quad (13)$$

下面来确定系数  $K$ . 由图3, 4电路分别有

$$\dot{U}_2 = jX_{ad} \dot{I}_1 - j(X_{ad} + X_{fkd}) \dot{I}_2, \quad \dot{U}_2' = jX_{ad}' \dot{I}_1' - jX_{ad}' \dot{I}_2'. \quad (14)$$

将  $\dot{I}_1 = \dot{I}_1', \dot{I}_2 = \dot{I}_2' / K, \dot{U}_2 = K \dot{U}_2', X_{ad}' = K X_{ad}$  代入式(14), 可得

$$\dot{U}_2 = jX_{ad} \dot{I}_1 - jX_{ad} \dot{I}_2 / K. \quad (15)$$

比较式(14)与式(15), 可得  $X_{ad}/K = X_{ad} + X_{fkd}$ , 则

$$K = X_{ad} / (X_{ad} + X_{fkd}). \quad (16)$$

至此, 由式(5), (6), (7), (10), (13)和式(16), 可即得图4简化电路的参数.

### 3 结束语

对于计及励磁绕组与阻尼绕组之间互漏感的改进同步电机模型, 按保持定子电压、电流不变, 维持变换网络两边电路的功率不变进行简化. 所得简化电路, 与传统的不计上述互漏感时的模型电路结构相同. 依据简化模型, 可以借用传统的分析同步电机特性的解析公式, 计算同步电机(改进模型)的时间常数和运算阻抗等, 使定量、定性分析计算工作大为简化.

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## Simplifying the Equivalent Circuit in the Improved Model of Synchronous Electric Machines

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**Abstract** It is necessary for setting up an integrated model of synchronous electric machines to calculate mutual leakage inductance between field winding and damping winding. As the introduction of mutual leakage inductance will complicate analysis and calculation and will lead to failure of traditional formulas of analysis and calculation, the author poses transformation condition of stator side and rotor side, and properly simplifies the improved model of synchronous machines to which the mutual leakage inductance between field winding and damping winding has been introduced. The simplified model is similar to the traditional model of synchronous machines which takes no account of mutual leakage inductance, thus the analytical method of traditional model and its formula may also be used in analysis and calculation.

**Keywords** synchronous machines, equivalent circuit, network transformation